Fundamental Issues of Lean Premixed H_2/air Combustion for Gas Turbine Development

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Objective & Approach of LBNL DOE-FE Project

- **Objective**
  - **Explore the feasibility of the low-swirl combustion concept for lean premixed syngas and H_2 turbines**
- **Approach**
  - **Adapt low-swirl combustion for energetic H_2 fuels**
    - **Scale up nozzle design to larger sizes & throughputs**
    - **Optimize swirler for syngas and H_2 operation**
    - **Consider fuel-flexible options**
  - **Address flashback and auto-ignition risks**
    - **Develop fuel injection and mixing strategies**
    - **Investigate turbulent flame speed and flashback mechanism**

Current Status

- **Developing a first-order analytical model for the turbulent flame brush position**
  - **Linking swirl number to flame position, flowfield features, turbulent flame speed, and turbulence**
  - **Foundation for assessing performance and guiding hardware design**
- **Investigated H_2/air flames at STP**
  - **Optimized LSI to operate with pure and diluted H_2 reactants**
    - **Requires a slightly lower swirl number than for hydrocarbons**
  - **Found linear turbulent flame speed correlation for H_2**
- **Testing with high H_2 fuels at NETL**
  - **Applied knowledge from laboratory studies in the prototype design**
- **Preparing tests with syngas and H_2 at Georgia Tech**
- **Initiated collaboration with Siemens Power Generation**

Scientific Foundation Needed for Hardware Development

- **Basic understanding of the overall flame and flowfield behaviors at turbine conditions**
  - Validate first-order analytical model and establish engineering guidelines for H_2 and syngases
    - Limited knowledge of LSC compared to the wealth of information on high-swirl combustion
  - Gain physical insights to address system integration issues and reduce design iterations
- **Detail characteristics of laminar and turbulent flames**
  - Develop turbulent flame model for lean premixed syngas and H_2
    - Characterizing fuel effects on local heat release
  - Support development of predictive computational tools
    - High fidelity numerical simulations with detail chemistry that capture the entire flowfield, the flame, and its emissions
      - Limited capability of RANS CFD due to its averaged nature
      - Standard LES based on typical flame models not applicable

Low-Swirl Burner Is An Effective Tool to Address Fundamental Issues

LBNL/Lund/Darmstadt LSB for fundamental premixed turbulent flame studies

- **Provides a close approximation of a locally planar 1D premixed turbulent flame**
  - **Adopted by researchers world-wide**
- **Laboratory data directly relevant to gas turbine development**
  - **Research burners and gas turbine hardware have the same configuration**
  - **Laboratory flame properties and behaviors similar to those observed at turbine conditions**
    - **Better understanding of this link will greatly facilitate development for H_2 turbines**

Fundamental Issues For LSC Development

- Ignition delay
- Combustion dynamics
- <u>LSC flowfield evolution with velocity, temperature & pressure</u>
- <u>Turbulent flame speed</u>
- Properties of lean laminar syngas and H_2 flames
- Chemical kinetics (molecular transport and rate coefficients) of lean H_2 and syngas systems
- Heat release models for H_2 and syngas turbulent premixed flames at relevant turbine conditions
- NO_x formation
- Turbulence models for swirling flows
- Computational methods for turbulent reacting flows

Issues Being Addressed by Current Project

Laboratory Experiments on Premixed H_2 Flames

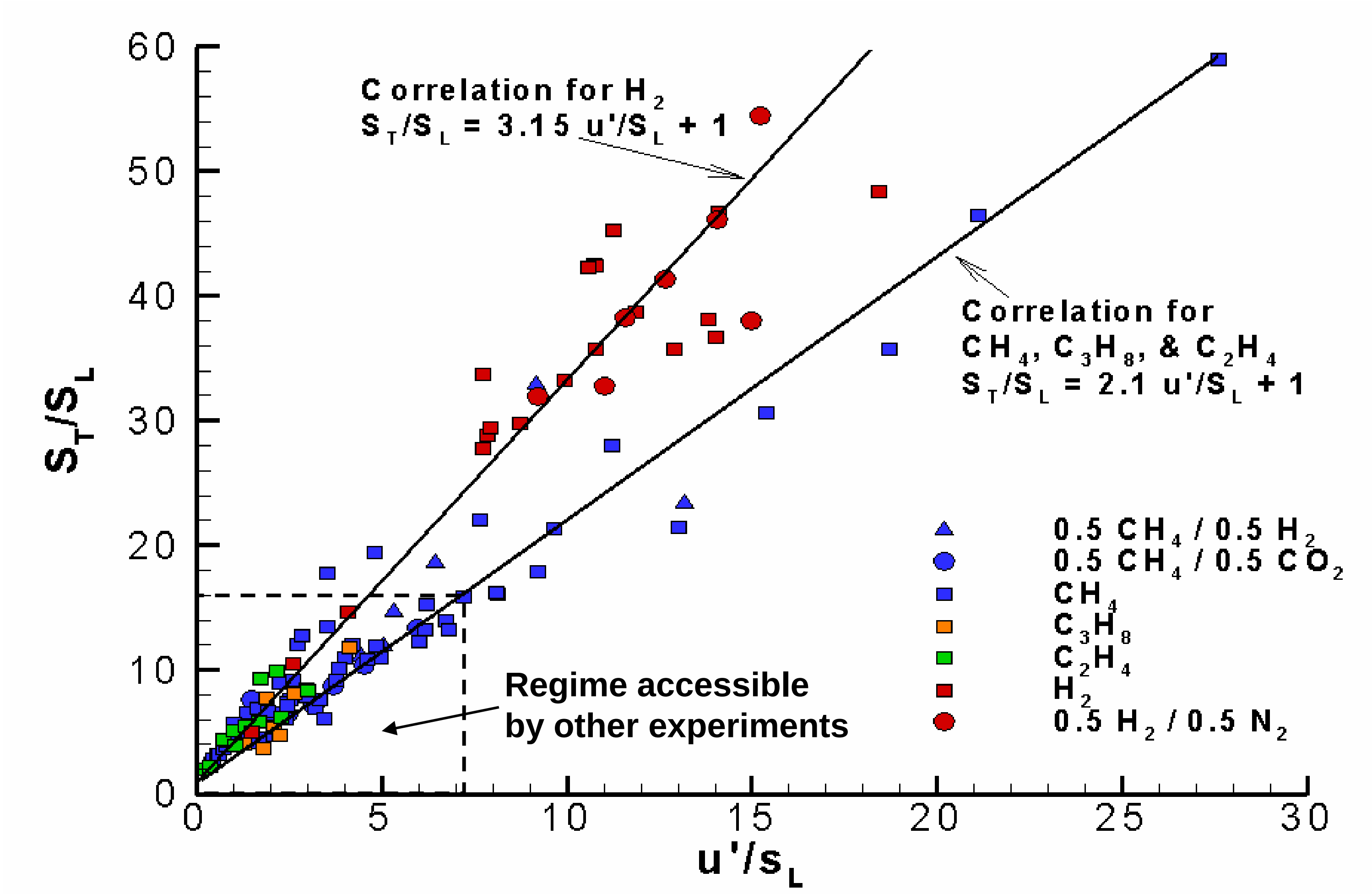
Lean premixed H_2/air flame at $\phi = 0.35$ & $U_0 = 20$ m/s captured by an IR camera

- **Provide basic knowledge to configure LSC for H_2 turbine**
- **Studied flames burning with pure H_2 and H_2 diluted with 25% and 50% N_2 dilution (by volume)**
  - Conditions with T_{ad}= 13800, 1320, 1200 K
- **Varied swirl number from 0.57 < S < 0.41**
  - Varied the blockage ratio and geometric pattern of the center plate
- **Measured lean blow-out and flowfield characteristics at $9 < U_0 < 20$ m/s**
- **Found optimum configuration for H_2**
- **PIV measures S_T and other flowfield characteristics**

Turbulent Flame Speed Central to the Low-swirl Combustion Concept

- **Lifted flame exemplifies propagating nature of premixed combustion**
- **Correlation of turbulent flame speed, S_T, with turbulence intensity provides empirical constant for the LSC analytical model**
- **4 different ways to define turbulent flame and each has its own specific meaning:**
  1. **Local displacement flame speed – most relevant to LSC**
  2. **Averaged displacement flame speed – bomb experiments**
  3. **Local consumption flame speed**
  4. **Averaged consumption flame speed – conical flames**
  - **Comparison and interpretation of S_T from different definitions are counter-productive**
- **Local turbulent displacement flame speed at the axis most important to LSC**
  - **Flame speed at the stabilization point and flashback origin**
    - **Laboratory measurements and correlation of S_T give insights into flashback, fuel effects, and assist the design of fuel-flexible swirlers and injectors**
    - **Lacking data at turbine conditions**

S_T of H_2 Flames Show Linear Correlation



Implication of S_T Correlation

- **Local turbulent displacement flame speeds measured in low-swirl combustion systems are significant higher than the averaged displacement flame speeds measured in non-stationary flames and the averaged consumption flame speed measured in stationary flames**
  - **Averaged flame speed inadequate for assessing flashback risks**
  - **Local flame speed at the flashback origin is most useful**
- **50% difference in H_2 and CH_4 turbulent displacement flame despite significant difference in laminar flame speed**
  - **Correlation equations show contribution from laminar flame speed becoming insignificant at high u'**

Need H_2 Turbulent Flame Speed Correlation at Relevant Gas Turbine Conditions

- **Significant experimental challenges for laser anemometry measurements in high-pressure flow channels**
  - **Transmitting laser and scattered signal through windows reduces signal to noise**
  - **Operational difficulties associated with cleanup of fine particles deposited on windows**
- **University and National Lab researchers rising to this challenge**
  - **Overall trend can be inferred by observing LSI H_2 flames at high T and P**
  - **Detailed measurements at selected data points for quantitative comparison with results from STP laboratory experiments**

Open Issues

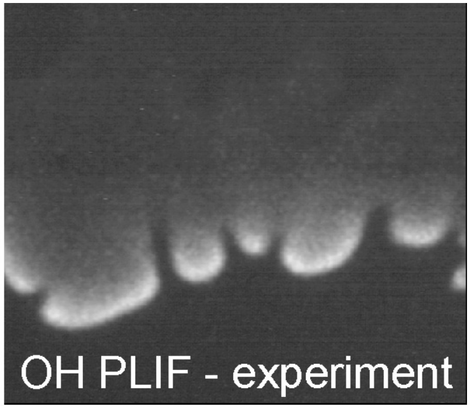
Limited Data Available For Lean H_2 Laminar Flame Speeds

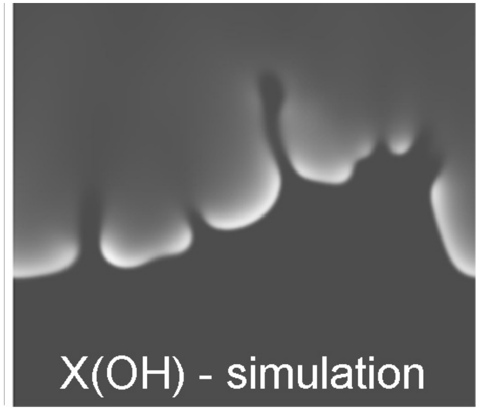
- **Laminar H_2/air premixed flames are inherently unstable for $\phi < 0.7$ due to thermo-diffusive Instability**
  - **Cellular flame structures studied experimentally and theoretically**
- **Instability affects measurements of laminar flame speed S_L**
  - **Bomb experiments requires corrections to obtain un-stretched laminar flame speed**
  - **Counterflow burner generates positive stress to suppress thermo-diffusive instability**
- **Chemical kinetics schemes for lean H_2/air flames under predict measured S_L**
  - **Huge scatter in predicted S_L of lean H_2 flames**
  - **Rate constants for third body reactions and molecular transport coefficients need further studies**
- **Large uncertainties exist for a basic property needed to analyze LSC flame processes**
  - **Affects the accuracy of the S_T correlation coefficient but not its linearity**

Reaction Front Instability Affecting H_2/Air Turbulent Premixed Flame

- **Turbulence produces both positive and negative stretch**
  - **Suppression and promotion of reaction front instability control how H_2 flames respond to turbulence**
  - **Variations in reaction front structures and its wrinkle topology dictate local heat release rates and it spatial distribution**
- **Pressure increases thermo-diffusive instability**
  - **Coupling of pressure & turbulence effects remains unexplored**
- **Turbulence time scales can be much faster than preferential transport time scales**
  - **Can high turbulence suppress thermo-diffusive instabilities?**
- **Significant implication on turbulent flame model**
  - **Stretched laminar flamelet model cannot be applied to lean H_2 turbulent flames**

Understanding and Characterizing Lean H_2/Air Premixed Turbulent Flames





- **Research Need**
  - **Evolution of preferential diffusion effects with turbulence intensity, temperature and pressure**
  - **Development of heat release model for LES and CFD**
- **Opportunity**
  - **Coordinated experimental and computational investigations of premixed turbulent flame structures**
    - **Preliminary results obtained from OH-PLIF measurement and 3D time dependent simulation of H_2/air flames in LSB**
      - **Wrinkle topology is drastically different than those of hydrocarbon flames**
      - **Non-uniform heat release with significant enhancement and local extinction due to thermo-diffusive instability are evident on the experimental and computational results**

Characterizing H_2/Air Reaction Zone Structures

- **Research Needs**
  - **Understand the different responses to positive and negative stretch**
    - **Only positively stretched laminar flames have been studied**
    - **Very limited knowledge on negatively stretched flame with local extinction**
  - **Improve species transport in chemical kinetic scheme**
- **Opportunity**
  - **Controlled 2D oscillating laminar flame experiment generating regular and stationary flame wrinkles for detailed interrogation by laser methods**
    - **Stationary flame wrinkle structures amenable to diagnostics**
    - **Ideal for low Mach Number simulation with adaptive mesh refinement**
  - **Test bed for studying effects of preferential diffusion on unsteady flame characteristics and chemistry/turbulence interactions**
    - **2D flowfield reduces experimental ambiguities for direct comparison with simulations**

Predicting NO_x Emissions at Turbine Conditions

- **Research Need**
  - NO_x emissions difficult to predict
    - Temperature and pressure dependencies of N_2 chemistry
    - Log linear dependence of LSC NO_x on T_{ad} regardless of fuel, T and P
      - Why does this dependency exists?
      - When does this dependency breakdown?
- **Opportunity**
  - Need improved understanding of NO_x formation in ultra-lean flames and the influence of the flowrfield
  - Experimental and computational study to obtain a scientific underpinning
    - Comparing NO_x contours in high-swirl and low-swirl combustors
    - Correlate recirculation zone strength with NOx concentrations
    - Compute NO_x dependency on residence time at STP and at high T and P

Combustion Dynamics

- **Research Needs**
  - **Response of LSC to external excitations**
    - **Lifted flame and absence of strong recirculation affect the responses**
      - **LSI in T70 engine shows different acoustic signature**
      - **Acceptable pressure fluctuations at frequencies different than SoLoNOx high-swirl injectors**
- **Opportunity**
  - **Side-by-side comparison of low-swirl combustion and high-swirl combustion subjected to the same acoustic forcing and fuel/air fluctuations**
    - **Fresh insights to understand combustion dynamics**
    - **Model for LSC oscillations**
    - **Collaboration with Universities and National Laboratories researchers**

Merging Measurements, Chemistry, Models & Simulation

- **Research Need**
  - **Computational tools to predict LSC flame and flowfield properties and their coupling with combustor geometries**
- **Opportunity**
  - **Establish a benchmark experimental and computational configuration**
    - **Side-by-side comparison of low-swirl and high-swirl combustion in a gas turbine simulator with well-defined boundary conditions**
  - **Promote cooperation among experimentalists, computational scientists and tool developers**
    - **Evaluate capabilities and weaknesses of RANS, LES, LMC and DNS**
    - **Define experimental configuration with well defined input, side and exit boundaries**
    - **Obtain benchmark data to calibrate and improve the computational methods**
    - **Develop robust flame and turbulence models**
  - **Improve predictive capability for LSC including flame volume and flame chamber interaction**

Summary

- **Principle of LSC is described by a top level model that can be used to guide its scale-up for large utility turbines**
  - **Laboratory experiments are being performed to provide empirical inputs for hydrocarbons, syngas and hydrogen**
- **Development for syngas and H_2 turbines requires basic knowledge on the combustion properties of lean syngas and H_2 flames**
  - **Well-designed experiments and coordinated theoretical and numerical studies are critical to provide new insights on both laminar and turbulent premixed flames**
    - **Reaction zone structures and wrinkle topology of turbulent flames**
    - **Positively and negatively stretched laminar flames**
  - **Coordinate and merge knowledge from University and Nat'l Lab researchers**
    - **Ignition delay and combustion dynamics studies**
    - **Benchmark experiments at gas turbine conditions**
    - **Computational model for LSC**
  - **Share results with OEMs and vendors**